PULSE WIDTH, FREQUENCY AND HEIGHT CONTROL IN A TRANSISTOR BLOCKING OSCILLATOR

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ABSTRACT. A transistor blocking oscillator gives a sequence of rectangular pulses of identical height, width and spacing. Modified forms of such transistor blocking oscillators are described with a view to control pulse width, frequency and height thereby increasing the versatility of the circuit. Expressions for these quantities have been derived and confirmed by experimental results.

INTRODUCTION

A free-running transistor blocking oscillator gives a sequence of rectangular pulses of identical height, width and spacing. Its versatility is greatly increased if these parameters can be controlled in a smooth and continuous fashion. The present paper considers some modifications of the basic transistor blocking oscillator circuit to meet these requirements.

The modification described to control the pulse width includes an emitter follower in the feedback loop of the blocking oscillator. The technique permits the production of relatively longer pulses, the width of which can be controlled by means of an external resistance in the emitter circuit of the oscillator. A theoretical relation giving the pulse width as a function of this resistance and other related parameters has been derived and found to be reasonably reliable as revealed by experimental results. An experimental circuit designed on the above ideas permitted a 6 : 1 variation in pulse width as against a 2 : 1 variation obtained with a simple blocking oscillator without the emitter follower.

Methods devised to enable control of amplitude and frequency of the generated pulses independent of each other consisted in introducing in the basic blocking oscillator circuit a biased diode and a linearising arrangement permitting a constant current discharge of the condenser. The height and frequency were found to have linear dependences upon the appropriate control voltage. Since the variations were linear and independent of each other, these could be used to obtain a faithful modulation of either amplitude or frequency. It has also been pointed out that the arrangement offers the possibility of analogue multiplication of two independent parameters x and y used as the two control voltages.

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Linvill and Mattson (1955) were the first to give a comprehensive picture of the operation of a transistor blocking oscillator and the analysis given by them still remains outstanding because of its simplicity and directness of approach. Since the present paper follows closely the treatment given by these authors, it is desirable to restate first the relevant portion of the analysis in some detail.

ANALYSIS OF TRANSISTOR BLOCKING OSCILLATOR BY LINVILL AND MATTSON

For convenience in analysis, the operation of a transistor blocking oscillator is divided into two parts viz, (1) the regenerative period and (2) the ON period of the oscillator. We shall consider only the ON period in the following and introduce the expression for the pulse width of the basic blocking oscillator as given by Linvill and Mattson

The transistor blocking oscillator is shown in Fig. 1 and its equivalent circuit during the ON period in Fig. 2. During this period, the current gain of the tran-

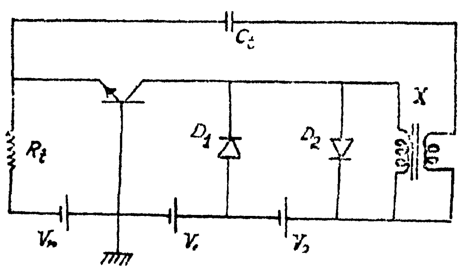

Fig. 1. The Transistor Blocking Oscillator.

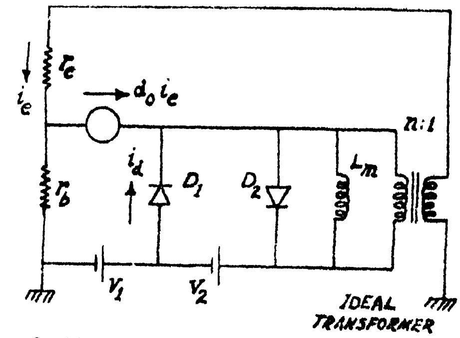

Fig. 2. Circuit Approximant of the Transistor Blocking Oscillator during the ON Period

sistor can be approximately treated as a constant and the effect of the leakage inductance of the transformer and the collector capacitance of the blocking oscillator transistor may be neglected. The diode D_1 represents a short circuit and D_2 an open circuit. Referring to Fig. 2, it can be seen that at the termination of the switching period, the magnetising inductance L_m does not carry appreciable current, though the voltage V_2 is applied directly across it through the diode D_1. The emitter current i_e is obtained by considering a voltage V_2/n (where n is the transformer turns ratio) on the secondary side driving the current through the effective resistance at the emitter point, which is $r_e+r_b(1-\alpha_0)$, where r_e: emitter resistance, r_b : base resistance and α_0 : grounded base current gain of the transistor. Thus we get,

$$i_e = \frac{V_2}{n[r_e+r_b(1-\alpha_0)]} \tag{1}$$

The current entering the transformer primary is of course i_e/n. The diode current through D_1 at the outset is given by the difference between the collector current (obtained as $\alpha_0 i$) and the current entering the transformer and is obtained as

$$i_d = \frac{V_2}{n[r_e + r_b(1-\alpha_0)]}\left[\alpha_0 - \frac{1}{n}\right]. \tag{2}$$

The pulse width τ_L is the time required for this amount of current to build up in the magnetising inductance L_m. The build up of current in the inductance L_m due to the constant voltage source V_2, effectively connected across it through D_1, is obviously linear with time. Thus, denoting this current by $i(t)$, we get,

$$i(t) = \frac{V_2}{}\, t. \tag{3}$$

Equating (2) and (3), the pulse width is obtained as,

$$\tau_L = \frac{(\alpha_0 n - 1)L_m}{n^2[r_e + r_b(1-\alpha_0)]}\,. \tag{4}$$

It may appear from eqn. (4) that pulse width variation could be effected by controlling r with the help of emitter current. However, since the emitter (or collector) current in a switching circuit is practically controlled by the external load on the collector an attempt at effecting such a variation proves to be futile. The only way to vary effective r_e would be to introduce additional feature in the basic blocking oscillator circuit shown in Fig. 1.

MODIFIED TRANSISTOR BLOCKING OSCILLATOR CIRCUIT FOR PULSE WIDTH CONTROL

The circuit consists essentially of a transistor blocking oscillator, the feedback path of which includes a transistor S_2 proceeding the transformer X (Fig. 3). The primary function of S_2, arranged in the form of an emitter follower, is to decrease the instantaneous balancing current $i(t)$ flowing through the diode D_1 and the base of transistor S_2. The diode current i_d is the initial switching current flowing through D_1 and the transistor S_1—the process being the same as in the conventional Linvill and Mattson oscillator as described earlier. Since, however, the current $i(t)$ is less and hence the time taken for balancing longer, the pulse duration also is much longer. In the following, we deduce an expression for the duration of the pulse thus lengthened.

The modified blocking oscillator circuit as shown in Fig. 3 is arranged to work from external trigger pulses—a triggered configuration being found necessary for accurate measurement of pulse width. When a trigger pulse of right polarity arrives at the input (i.e. the cathode of the diode D_3), the regenerative feedback, via the transistor S_2 and the transformer X, switches the oscillator transistor S_1 to the ON state. At this point the diode D_1 conducts and clamps the collector S_1 to the voltage E_2. Also since the diode D_1 is short, the constant voltage source

E_1 is effectively connected at the input of the emitter follower S_2. Taking the voltage gain of the emitter follower to be unity, it is easy to see that the input

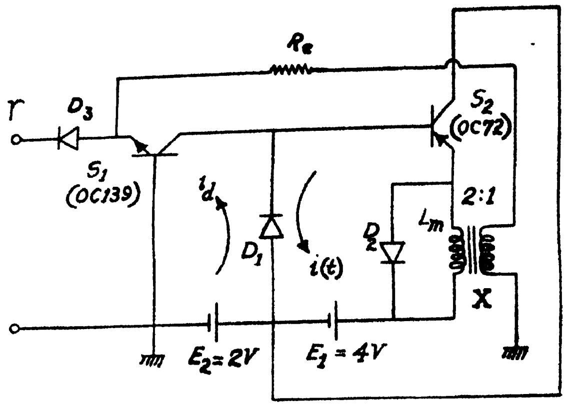

Fig. 3. Modified Transistor Blocking Oscillator Circuit for Pulse Width Control.

voltage E_1 appears undiminished at the output, i.e., accross the primary terminals of the transformer X.

Following Linvill and Mattson 1955, it is easy to show that

$$i_e = \frac{E_1}{n} \cdot \frac{1}{[R_e + r_e + r_b(1-\alpha_1)]}, \quad \ldots (5)$$

$$i_c = \frac{\alpha_1 E_1}{n[R_e + r_e + r_b(1-\alpha_1)]}, \quad \ldots (6)$$

where i_e ; current flowing through the emitter of S_1,
i_c : current flowing through the collector of S_1,
R_e : external resistance in series with the emitter of S_1,
r_e : emitter resistance of S_1,
r_b : base resistance of S_1

and α_1 : low frequency grounded base current gain of S_1.

Denoting the current flowing through the secondary of the transformer by i_e, that entering the primary is obsviously i_e/n, n being the transformer turns ratio. If the grounded emitter current gain of the transistor S_2 be denoted by β_2, the base current i_b required to maintain the emitter current will be given by

$$i_b = \frac{i_e}{\beta_2 n}$$

or,

$$i_b = \frac{E_1}{\beta_2 n^2[R_e + r_e + r_b(1-\alpha_1)]}. \quad \ldots (7)$$

Thus the diode current is given by

$$i_d = (i_c - i_b) = \frac{E_1}{n[R_e+r_e+r_b(1-\alpha_1)]}\left(\alpha_1 - \frac{1}{\beta_2 n}\right). \quad \ldots \quad (8)$$

Again, since the voltage across the primary of the transformer is E_1, the current through the magnetising inductance L_m of the primary will rise linearly with time giving

$$i_L = \frac{E_1}{L_m} t, \quad \ldots \quad (9)$$

where i_L : current through L_m.
and t : time.

The current flowing through the base of S_2, due to the magnetising current i_L at the emitter, is obviously $\frac{i_L}{\beta_2}$. Denoting this current by $i(t)$ we may write from eqn. (9)

$$i(t) = \frac{E_1}{\beta_2 L_m} t. \quad \ldots \quad (10)$$

Proceeding after Linvill and Mattson (1955) one gets from eqns. (8) and (10),

$$\tau = \frac{\beta_2 L_m}{n[R_e+r_e+r_b(1-\alpha_1)]}\left(\alpha_1 - \frac{1}{\beta_2 n}\right), \quad \ldots \quad (11)$$

where τ : pulse duration.

Since for a junction transistor $\alpha_1 \simeq 1$, $\frac{1}{\beta_2 n} << \alpha_1$ and $r_b(1-\alpha_1) \sim 0$, eqns. (11) may be re-written as

$$\tau = \frac{\beta_2 L_m}{n(R_e+r_e)} \quad \ldots \quad (12)$$

Eqn. (12) is more convenient than (4) in so far as it involves a new parameter R_e which can be used for controlling the duration τ in a simple manner.

MODIFIED CIRCUIT FOR PULSE REPETITION FREQUENCY AND HEIGHT VARIATION

The modification of the original Linvill and Mattson transistor blocking oscillator for independent control of pulse repetition frequency and height is shown in Fig. 4. In this, the transistor S_1, together with the feedback transformer X, constitutes the usual transistor blocking oscillator. The new feature introduced is a second transistor S_2 (of the *n-p-n* type) acting as a constant current device. Also, experience had shown that the hole storage effect due to saturation is negligible for low power transistors and hence the clamping diode used for eliminating saturation in the collector-base region of the transistor is not included in the present circuit.

During the time when the blocking oscillator is ON, condenser C charges to a positive value as usual. The discharge of this condenser determines the time after which the transistor S_1 again becomes forward-biased and gives a second pulse. Usually, this discharge time or the quiescent period of the blocking oscillator is determined by the leakage resistance and the bias voltage in series with it—the combination being shunted across C. In the present system, however, instead of this combination, the second transistor S_2, as mentioned above, is so arranged that a constant current discharge of C takes place.

In order to analyse the performance of the present circuit, we shall consider separately the aspects involving pulse frequency and pulse amplitude variation.

(a) *Pulse frequency variation* : It has been pointed out that the transistor S_2 allows a constant current discharge of C. This arises out of the fact that the collector current of a transistor is independent of collector voltage, base bias being kept constant. If now the working of the combination of the blocking oscillator and the constant current discharge device be so arranged that the quiescent period of the oscillator becomes much larger than the width of the generated pulse, then as will be presently shown, the repetition frequency of the pulses may be made to vary linearly with the variation of the voltage V_E (Fig. 4).

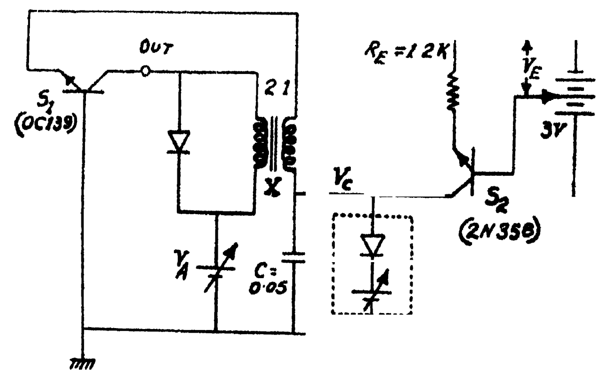

Fig. 4. Modified Transistor Blocking Oscillator Circuit for Pulse Frequency and Ampitude Control.

Referring to Fig. 4, if the voltage to which the condenser charges during the ON period of the blocking oscillator be denoted by V_c, then the time taken for the condenser to return to zero, i.e., the point where the oscillator is again turned on (actually the oscillator is turned on at a slightly negative potential) is obviously given by

$$\frac{i_c T}{C} = V_c,$$

or,

$$T = CV_c \qquad \text{... (13)}$$

where i_c : collector current of S_2

and T : quiecent period of the oscillator.

Again, considering the transistor S_2, the voltage across the emitter resistance R_E is given by,

$$v_e = V_E - V_{be}, \qquad \text{... (14)}$$

where V_{be} : voltage drop across the base-emitter junction.

Therefore the current i_e in the emitter circuit is found as

$$i_e = \frac{v_e}{R_E} = \frac{V_E - V_{be}}{R_E} \qquad \text{... (15)}$$

Eqn. (15) ignores the effect of the emitter resistance of the transistor which is made much smaller than the external resistance R_E. Also, denoting the grounded-emitter current gain of S_2 by β, the portion of i_e flowing through the base is given by

$$i_b = \frac{i_e}{\beta},$$

which in the light of eqn. (15), becomes,

$$i_b = \frac{V_E - V_{be}}{\beta R_E}, \qquad \text{... (16)}$$

where i_b : current flowing through the base of S_2.

Collector current i_c is given by the difference between the emitter and the base currents, i.e.,

$$i_c = i_e - i_b. \qquad \text{... (17)}$$

Combining eqns. (15), (16) and (17),

$$i_c = \frac{\beta - 1}{\beta} \cdot \frac{V_E - V_{be}}{R_E}. \qquad \text{... (18)}$$

Substituting eqn. (18) in (13), we get,

$$T = \frac{CV_c \beta R_E}{(\beta - 1)(V_E - V_{be})}. \qquad \text{... (19)}$$

As has been mentioned earlier, for small pulse widths as compared with the quiescent period, the frequency will be determined by T alone. Thus taking the inverse of eqn. (19), we get,

$$f=\frac{1}{T}=\frac{(\beta-1)(V_E-V_{be})}{CV_c\beta R_E}, \qquad \ldots \quad (20)$$

where f : pulse repetition frequency.

It is seen from eqn. (20) that, other parameters remaining constant, the pulse repetition frequency becomes linearly related with V_E, the base voltage of the discharging transistor S_2.

Incidentally, it may be recalled that according to eqn. (19), a linear variation of T is possible through variation in V_c. This may have use in certain special fields of application.

(b) *Pulse amplitude variation* : Considering the transistor blocking oscillator in Fig. 4 (shown inside the dashed enclosure), it may be seen that the amplitude of the generated pulse at the collector is equal to the supply voltage of the oscillator transistor S_1. Therefore, by injecting the control signal in series with the supply voltage, linear pulse amplitude variation could be directly obtained. The straightforward method has one drawback however. Since the voltage to which the condenser C charges depends upon the height of the generated pulse, the quiescent period and hence the repetition frequency of the oscillator also changes with change in supply voltage (eqns. 19 and 20) However, if an arrangement is made for holding the condenser voltage constant, the simultaneous change in frequency with amplitude variation may be avoided. This may be achieved by using a reference diode across the condenser, or, alternatively a biased diode may be used (shown within the dotted lines in Fig. 4). Since the cathode of the diode is biased positive, the diode remains open circuit as long as the voltage across the condenser remains smaller than the bias voltage. However, as soon as the voltage across the condenser rises above the bias voltage, the diode within the dotted lines becomes short circuit and clamps the condenser to the bias supply voltage. Thus V_c in eqn. (19) becomes equal to the bias supply voltage, thereby ensuring a fixed p.r.f.

RESULTS

(i). *Variation of Pulse Width*: The experimental circuit for the study of variation of pulse width is shown in Fig. 3 where the following values were used.

$$n=2, \quad L_m=150\mu\text{H}, \quad r_e=30\ ohms \text{ and } \beta_2=27.$$

(a) *Pulse width without emitter follower* : Pulse width as observed without the emitter follower S_2 was $\tau_L=1\mu$sec, the calculated value from eqn. (4) being 1.25μ sec. (taking $\alpha_0 \simeq 1$).

(b) ***Pulse width with emitter follower*** : The experimental values of τ when the emitter follower is included are shown in Table *I*. It may be seen that columns (3) and (4), giving the observed and calculated values as based on eqn. (12) lend sufficient support to the relevant theoretical deduction.

TABLE I

R_e (ohms)	(R_e+r_e) (ohms)	Pulse Duration τ (μ sec)	
		Observed	Calculated
35	65	31	32.4
45	75	26	27
55	85	24	23.8
70	100	19	20.3
100	130	17	15.5
150	180	11	11.3

(ii) *Variation of frequency* : The experimental circuit arrangement is shown in Fig. 4. The values of the various circuit parameters used are the following :

$$\beta = 30,\ C = 0.05\mu F,\ R_E = 1.2K\ \Omega \text{ and } V_{be} = 0.1 \text{ volt.}$$

Table II gives the results of experimental measurements of pulse frequency for the given circuit, in which the respective pulse periods are also included. The

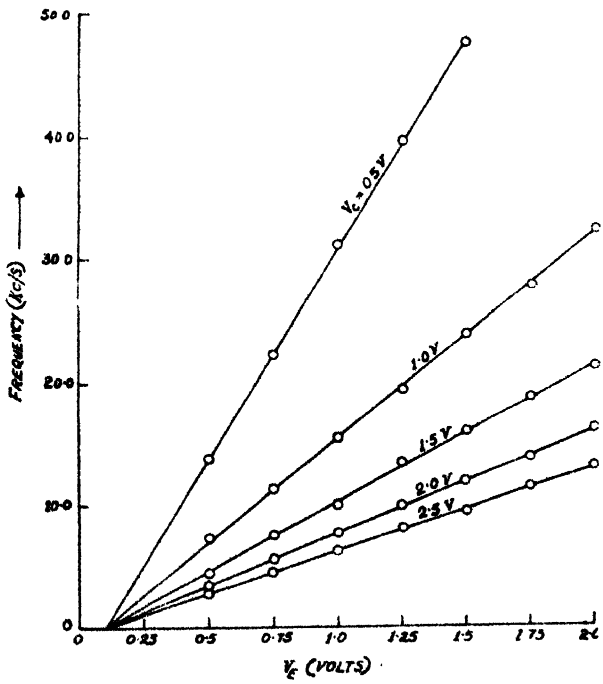

Fig. 5. Variation of Pulse Frequency.

nature of variation is shown graphically in Fig. 5 where the solid lines represent the theoretical curves with V_c as parameter and the small circles, the experimental results. It may be seen both from the table and the graphs that the agreement

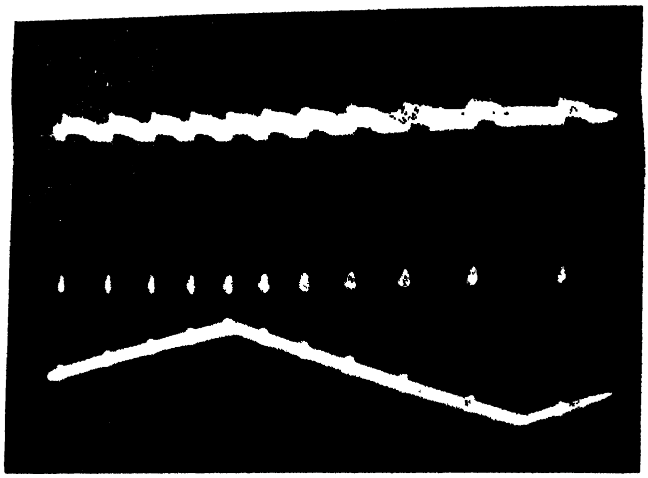

Fig. 6. Linear Frequency Modulation.

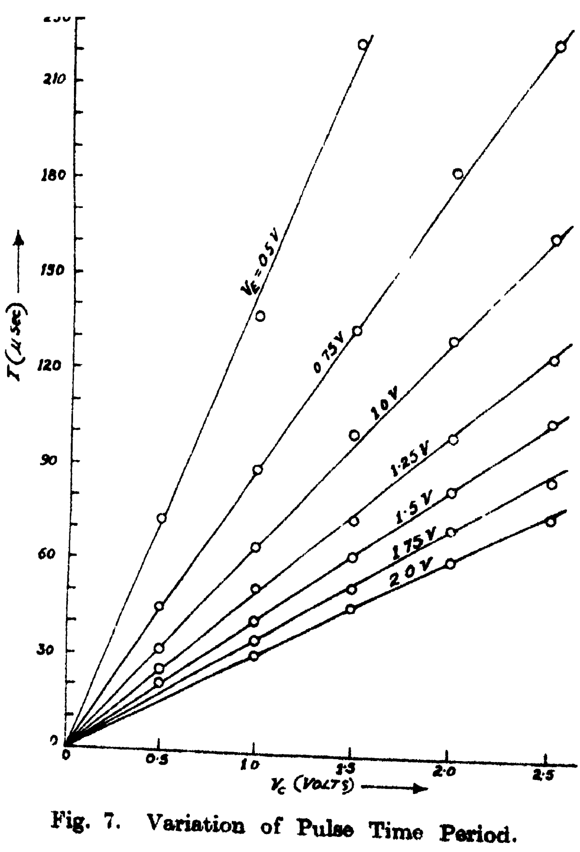

Fig. 7. Variation of Pulse Time Period.

between the observed and the calculated values as based on eqn. (20) is very good. This suggests the possibility of faithful pulse frequency modulation using the arrangement. The expected linear frequency modulation is illustrated by the oscillographic records shown in Fig. 6. It is seen that the amplitude remains a constant during the modulation cycle thereby implying independent variation of both the parameters.

In Fig. 7 are given the theoretical lines depicting the variation of T with V_c with V_E as a parameter. The corresponding experimental results are also given by small circles. Here again the experimental results appear to support the theoretical deduction.

TABLE II

V_0 (Volts)	V_E (Volts)	Frequency f(kc/s)		Pulse Time Period T(μ sec)	
		Theoretical	Experimental	Theoretical	Experimental
0.5	0.50	13.75	33.8	72.0	72.5
	0.75	22.25	22.3	44.5	45.0
	1.00	31.25	31.2	32.0	32.0
	1.25	39.64	39.8	25.0	25.2
	1.50	48.25	48.0	20.5	20.8
1.0	0.50	7.00	7.3	145	137
	0.75	11.25	11.3	89	88.5
	1.00	15.50	15.5	64.5	64.5
	1.25	19.75	19.5	50.5	51.3
	1.50	24.10	24.0	41.3	41.6
	1.75	28.35	28.0	35.5	35.8
	2.00	32.70	32.7	30.5	30.6
1.5	0.50	4.6	4.5	213	222
	0.75	7.5	7.5	133.5	133
	1.00	10.35	10.0	96	100
	1.25	13.2	13.5	75.5	74
	1.50	16.0	16.0	62.5	62.5
	1.75	18.9	19.0	52.5	52.6
	2.00	21.75	21.5	45.9	46.5
2.0	0.50	3.5	3.5	286	286
	0.75	5.6	5.5	178	182
	1.00	7.7	7.7	129	130
	1.25	9.8	10.0	100.5	100
	1.50	12.0	12.0	83.5	83.5
	1.75	14.1	14.0	71.5	71.5
	2.00	16.25	16.2	61.5	61.7
2.5	0.50	2.75	2.7	364	370
	0.75	4.5	4.5	223	222
	1.00	6.25	6.2	162	162
	1.25	7.9	8.0	125.5	125
	1.50	9.6	9.5	104	105
	1.75	11.5	11.5	88	87
	2.00	13.25	13.2	76.2	75.7

(iii) ***Variation of Amplitude*** : As has been mentioned in the previous section, the amplitude V_A of the generated pulse should be equal to the supply voltage

(Fig. 4). The results of experimental measurement of pulse amplitude as given in Table III confirm the expectation. This is shown graphically in Fig. 8. It was

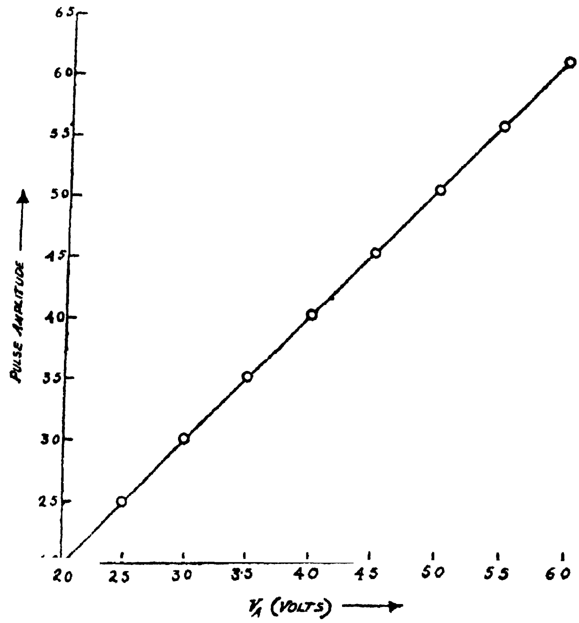

Fig. 8. Variation of Amplitude.

also found in this connection that the pulse repetition frequency remained unaffected with the variation of V_A—thereby enabling amplitude control independent of frequency. This is also demonstrated in Fig. 9 where the oscillographic record

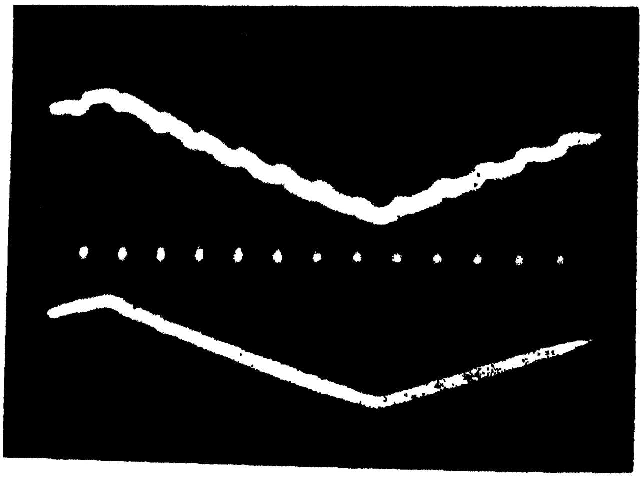

Fig. 9. Linear Pulse Amplitude Modulation.

reveals that the frequency remains unaltered (equal spacing of the pulses) while amplitude varies linearly with supply voltage.

TABLE III

V_A (Volts)	Pulse Amplitude	
	Theoretical	Experimental
2.0	2.0	2.0
2.5	2.5	2.5
3.0	3.0	3.0
3.5	3.5	3.5
4.0	4.0	4.0
4.5	4.5	4.5
5.0	5.0	5.0
5.5	5.5	5.5
6.0	6.0	6.0

DISCUSSIONS

Eqn. (12) shows that width of the generated pulse in a blocking oscillator with an emitter follower in the feedback loop is directly proportional to β_2. Hence, it was thought that pulse width modulation might be achieved by working the emitter follower at low collector voltages, the variation of which, in turn, might vary β_2. By actual measurement, however, no significant variation of β_2 could be obtained. The scheme for pulse width modulation was, therefore, abandoned. However, in the production of long pulses, the circuit appeared to have more flexibility than that of the Linvill and Mattson type. For the latter circuit eqn. (4) gives

$$\tau_L \simeq \frac{L_m}{nr_e} \tag{21}$$

for $\alpha_0 \simeq 1$ and $n >> 1$.

Comparing eqn. (21) with (12), which gives expression for pulse width with an emitter follower, it is seen that for a given total of the emitter resistance $(R_e + r_e)$, the pulse duration with an emitter follower in the feedback loop is β_2 times longer than τ_L, the duration in the Linvill and Mattson circuit. It is also easy to see that for the same pulse duration, the feedback transformer in the modified circuit has a much lower value of magnetising inductance than that which would be necessary in order to avoid pulse droop that would arise in the straightforward blocking oscillator circuits handling pulses of comparable width.

A second desirable feature, obtained through the introduction of the emitter follower, arises out of the fact that the circuit provides a low impedance output point. This also results in its capability of handling a greater load.

Coming to the consideration of manual control of pulse width by the vatiation of R_e in the emitter circuit of the blocking oscillator (as may be useful in laboratory equipments), it is easy to see that increasing R_e reduces regeneration of the blocking oscillator. This sets an upper limit of R_e, beyond which the blocking oscillator would not function. Since pulse width varies inversely with the resistance in the emitter circuit, the highest possible value of R_e corresponds to the minimum pulse width. Introducing a resistance R_e at the emitter end in the Linvill and Mattson oscillator too one could achieve width variation. For such an arrangement the highest value of R_e was found to be about 37 ohms giving a pulse width of 0.6μ sec (theoretical value as based on eqn. (4) with r_e replaced by r_e+R_e is 0.56μ sec, the r_e value under operating condition being about 30 ohms. Referring to 1(a) of the Results, the maximum limit of the generated pulse width is found to the 1μ sec (corresponding to $R_e = 0$). Thus the pulse width variation, obtainable in the Linvill and Mattson oscillator, lies in the range of 0.6μ sec to 1μ sec.

Now, reffering to the blocking oscillator with the emitter follower, it is seen that the loss of regeneration due to R_e is compensated for by the extra current gain provided by the emitter follower. It is, therefore, permissible to increase R_e to a much higher value corresponding to a much greater reduction of pulse width. However, introduction of the factor β_2 in the expression for pulse width increases the overall length of the pulse.

Taking a typical example, as given in Table 1, the range of pulse width variation is seen to be from 11.3μ sec. to 32.4μ sec. It may be mentioned that the upper limit for $R_e = 0$ corresponds to 67.5μ sec. Thus, it is seen by comparing the two blocking oscillator circuits that, so far as the percentage variation of pulse width is concerned, the modified circuit with the emitter follower in the feedback loop is distinctly superior to an ordinary Linvill and Mattson arrangement.

As has been seen in the preceding section, linear variation of pulse frequency and amplitude with independent voltages is possible. Figs. 6 and 9 suggest that the circuit as shown in Fig. 4 should be very suitable for effecting both pulse frequency and amplitude modulation.

Another possible application of the modified blocking oscillator circuit is in the field of analogoue multiplication. This results from that fact that both frequency and the amplitude of the train of generated pulses may be varied independently of each other. For, recalling that the output of an integrating circuit is proportional to the instantaneous amplitude v of each one of the individual pulses, the total output due to n pulses will be given by

$$Q = Knv, \qquad \ldots \quad (22)$$

where Q : total output of the integrating circuit
and K : factor of proportionality.

If the time integral corresponding to 1 second be considered, n becomes identical with frequency. Thus writing,

$$v = V(1+K_1x) \qquad \ldots \quad (23)$$

and

$$f = F(1+K_2y) \qquad \ldots \quad (24)$$

where V : pulse height in the absence of any external voltage.

x : external voltage expressed as a fraction of V and injected in series with V_A. This is one component of multiplication.

K_1 : constant of proportionality,

f : instantaneous pulse repetition frequency of the blocking oscillator,

F : pulse repetition frequency of the blocking oscillator in the absence of external voltage,

and K_2y : frequency change expressed as a fraction of F corresponding to second component of multiplication y in series with V_E,

one gets from eqns. (22), (23) and (24),

$$Q = KVF(1+K_1x)(1+K_2y),$$

or,

$$Q = KVF(1+K_1x+K_2y+K_1K_2xy). \qquad \ldots \quad (25)$$

Eqn. (25) shows that the integrator output consists of a steady term, two linear terms-one proportional to the first component of multiplication and the other to the second component—andfi nally the required product term. It is therefore clear that by balancing out the steady and the linear terms at the output of the integrator, one is left only with the desired product term proportional to xy.

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